

MASS PROPERTIES MEASUREMENT IN THE X-38 PROJECT

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ABSTRACT

This paper details the techniques used in measuring the mass properties for the X-38 family of test vehicles. The X-38 Project was a NASA internal venture in which a series of test vehicles were built in order to develop a Crew Return Vehicle (CRV) for the International Space Station. Three atmospheric test vehicles and one spaceflight vehicle were built to develop the technologies required for a CRV.

The three atmospheric test vehicles have undergone flight-testing by a combined team from the NASA Johnson Space Center and the NASA Dryden Flight Research Center. The flight-testing was performed at Edward's Air Force Base in California. The X-38 test vehicles are based on the X-24A, which flew in the '60s and '70s. Scaled Composites, Inc. of Mojave, California, built the airframes and the vehicles were outfitted at the NASA Johnson Space Center in Houston, Texas.

Mass properties measurements on the atmospheric test vehicles included weight and balance by the three-point suspension method, four-point suspension method, three load cells on jackstands, and on three in-ground platform scales. Inertia measurements were performed as well in which I_{xx} , I_{yy} , I_{zz} , and I_{xz} were obtained. This paper describes each technique and the relative merits of each.

The proposed measurement methods for an X-38 spaceflight test vehicle will also be discussed. This vehicle had different measurement challenges, but integrated vehicle measurements were never conducted. The spaceflight test vehicle was also developed by NASA and was scheduled to fly on the Space Shuttle before the project was cancelled.

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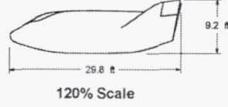
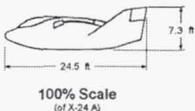
INTRODUCTION

The X-38 Project was initiated in early 1995 to develop the technologies for a vehicle that would be used as a crew return vehicle (CRV) for the International Space Station. The project used a combination of off-the-shelf systems and new technologies to develop a new human spacecraft for a fraction of the cost of past programs. Plans were to develop and build four operational X-38-based CRV's for less than half of what it cost to manufacture a single Space Shuttle orbiter.

The shape selected for the X-38's configuration was based on the X-24 lifting body. All of the lift necessary to maneuver and fly the X-38 comes from the flow of air over the body of the spacecraft and its fins. Lifting body configurations were studied extensively in the 1960s and 1970s as space entry vehicles. The shapes are good for reentry vehicles because of the large crossrange that can be obtained from the vehicle lift to drag ratio. The X-38 shape can achieve a crossrange of approximately 700 nm as compared to about 50 nm for the Apollo capsule. This gives the vehicle more landing opportunities per day than a capsule for a given number of landing sites. The large flat area on the bottom of the vehicle can also dissipate the heat seen during reentry. The family of lifting bodies all had very high landing speeds that proved difficult to control. To alleviate this problem a ram-air parafoil was added to the vehicle as the final descent mechanism. The combination of the lifting body for the high-speed part of entry followed by the parafoil for the final landing has proven to be a viable concept.

A series of test vehicles were built and tested to demonstrate the unique landing concept. Four atmospheric vehicles were built and tested in twenty (12 captive-carry, 8 drops) flight tests at NASA's Dryden Flight Research Center (DFRC). For those tests, the increasingly complex X-38 vehicles were released from a B-52 carrier aircraft at increasingly higher altitudes and Mach numbers. The flight tests were designed to intercept the trajectory of a CRV during reentry so the flight dynamics could be duplicated during the test. More tests were planned leading up to a spaceflight test of the X-38 when the X-38 Project was terminated. In the spaceflight test, an uninhabited space-rated vehicle under construction at NASA's Johnson Space Center (JSC) would have been released in orbit by the Space Shuttle to fly back to Earth. Figure 1 depicts the family of X-38 test vehicles. Vehicle 121 experienced a failure with its parachute system on its maiden flight and the remaining pieces were too small to reconstruct. Vehicles 131, 132, and 131-R were all flown successfully. Vehicle 131-R was undergoing a major system upgrade when the project was terminated. Vehicle 201 was the spaceflight test vehicle and it was estimated that the vehicle was over 85% complete at project termination. Most of the hardware had been installed and tested on vehicle 201. The vehicle successfully completed a cabin proof pressure test and a static structural test. Construction of Vehicle 133 was never initiated and Vehicle 301 was a designation for the first operational CRV that was to be built by a contractor after the successful test flight of vehicle 201.

**THE
X-38
FAMILY
OF
VEHICLES**



Vehicle 121 (Drop Vehicle)	Vehicle 131 (Inert Flight Vehicle)	Vehicle 132 (Free Flight Vehicle)	Vehicle 131-R (Free Flight Vehicle)	Vehicle 133 (Full Size Free Flight Vehicle)	Vehicle 201 (Space Flight Vehicle)	Vehicle 301 (Operational CRV)
100 % Scale	100 % Scale	100 % Scale	100 % Scale	120 % Scale	120 % Scale	120 % Scale
X-24 A Shape -No Fins	X-24 A Shape	X-24 A Shape	Modified X-24 A Shape	Modified X-24 A Shape	Modified X-24 A Shape	Modified X-24 A Shape
C130 Drop	B52 Drop	B52 Drop	B52 Drop	B52 Drop	STS Transport to LEO	STS Transport to ISS
Fiberglass Structure	Fiberglass Structure	Fiberglass Structure	Fiberglass Structure	Fiberglass Structure	Aluminum/Composite Structure	Aluminum/Composite Structure
7350 Sq. Ft. Parafoil	5400 Sq. Ft. Parafoil	5400 Sq. Ft. Parafoil	7500 Sq. Ft. Parafoil	7500 Sq. Ft. Parafoil	7500 Sq. Ft. Parafoil	7500 Sq. Ft. Parafoil
JSC Instrumentation	JSC Avionics & Instrumentation	JSC Avionics & Instrumentation	JSC Avionics & Instrumentation	JSC Avionics & Instrumentation	Complete Spaceflight Vehicle Systems	Complete Spaceflight Vehicle Systems
Fixed Aerosurfaces	Fixed Aerosurfaces	Active Aerosurfaces	Active Aerosurfaces	Active Aerosurfaces	Active Aerosurfaces	Active Aerosurfaces
		JSC Flight Control	JSC Flight Control	JSC Flight Control	Pressurized Cabin	Pressurized Cabin
			New Aero- dynamic Shape	Fullscale Parachute Integration	Deorbit Propulsion Stage (DPS)	DPS
Accomodations for Crew of 7.						

Figure 1 - Family of X-38 Vehicles

MASS PROPERTIES MEASUREMENT BACKGROUND

To aid the reader in terminology that is used in this paper a description of the vehicle coordinate system is provided. The x-axis of the vehicle is positive going from the nose to tail of the aircraft. Therefore, the X_{cg} is the longitudinal center of gravity (CG) and I_{xx} is the roll inertia. The vehicle y-axis is positive out the right side of the aircraft and the z-axis was positive from the bottom of the vehicle to the top of the vehicle. Therefore, the Y_{cg} is the lateral CG and the Z_{cg} is the vertical CG. I_{yy} is the pitch inertia and I_{zz} is the yaw inertia.

Measuring the mass properties of the test vehicles provided some challenges. The vehicles have a landing skid system that reduces the landing loads on the vehicle, but the skids are not designed to support the vehicle weight. Therefore, vehicle weight and CG must be obtained by suspending the vehicle or placing it on jackstands. Accurate knowledge of the jackpoints and liftpoints is required to accurately calculate the mass properties from test measurements. Knowledge of the vehicle inertias was desired, but the vehicles were too large for spin tables. Traditional methods utilizing suspension, springs, and significant amounts of fixturing were employed.

Each test vehicle had slightly different measurement test requirements and associated challenges. Vehicle 131 was the first vehicle to be dropped from the B-52. This vehicle did not include an active flight control system. The rudders and body flaps were pinned in a fixed position. There was a concern that when the vehicle was released from the B-52 that aerodynamic interference from the mothership would cause the test vehicle to yaw substantially. If the products of inertia were not correct, the yaw could induce a large roll producing a loss of control condition or interfere with the parachute deployment sequence. Therefore, it was essential to have accurate knowledge of the moments of inertia to ensure acceptable flight dynamics. The atmospheric test vehicle airframes were built primarily out of fiberglass with wood cores. Aluminum bulkheads and steel fittings for the parachutes were used for areas of high loading. The inertias were estimated since no CAD models of the airframes existed. To reduce the risk associated with the first flight it was decided that the vehicle weight, three-axis CG, and the critical inertias, I_{zz} and I_{xz} would be confirmed by measurement.

Vehicle 132 was the second atmospheric test vehicle to undergo flight tests and it had an active flight control system. Electromechanical actuators (EMA's) powered by batteries moved the flight control surfaces. With the addition of the highly tuned active flight control, the aerodynamic interference of the B-52 was not as much of a concern. However, to extract the vehicle aerodynamic coefficients accurately from the flight data, it was determined that detailed knowledge of the vehicle inertias was required. The aerodynamic coefficients can be determined from flight testing by measuring vehicle rates and accelerations provided the vehicle mass properties are well known. The aerodynamic database for vehicle 132 was determined via wind tunnel testing, which carries with it associated uncertainty levels. Flight derived aerodynamics would provide confirmation of the test derived database and validate the appropriate uncertainty levels. Therefore, I_{xx} and I_{yy} were measured in addition to the mass properties measurement tests that were performed on vehicle 131.

Once vehicle 132 began flight-testing vehicle 131 was returned to the airframe manufacturer where a new aerodynamic upper surface was installed over the old one. The new shape was agreed upon by NASA and the European Space Agency (ESA) to provide more internal volume for a larger crew complement and increased stiffness to the vehicle so it could be launched on an expendable launch vehicle. To get early knowledge of the aerodynamics and flight control of this new vehicle shape vehicle 131 became vehicle 131-R after the new transformation. A similar flight test program to confirm the vehicle's aerodynamic characteristics was initiated. Vehicle 131-R underwent the same measurement tests as vehicle 132.

The spaceflight vehicle, which has fragile thermal protection system tiles, provides new challenges in mass properties measurement. The procedures for measuring the mass properties for vehicle 201 were never finalized. A new method for measuring mass properties called the dynamic inertia method (DIM)¹ was proposed for obtaining the spaceflight vehicle mass properties. This method was utilized on two of the atmospheric test vehicles and the techniques were being matured so that DIM could be used on the spaceflight vehicle without also having to do traditional inertia swings.

In all over 30 major measurement tests were performed on the family of X-38 test vehicles. The following sections describe each type of major test performed during the course of the project.

WEIGHT AND CENTER OF GRAVITY MEASURMENT

During the course of the build-up of the atmospheric test vehicles, the vehicle weight and CG were measured several times. The method of testing selected was determined by the facilities available and the accuracy required for Zcg. Measurement of the vehicle weight is relatively straightforward as is the determination of Xcg and Ycg. Measurement of the Zcg requires the vehicle to be articulated in the longitudinal direction on the order of $\pm 20^\circ$ from vehicle level. Data collection at several pitch angles allows the calculation of the Zcg. The degree in difficulty in obtaining the Zcg measurement makes one question the need for doing the test in the first place. If the vehicle is not overly sensitive to the Zcg location then a calculated value may be acceptable.

The X-38 test vehicle flight dynamics were sensitive to Zcg so efforts were made to measure it as accurately as possible. Baseline Zcg measurements were performed on the vehicle airframes initially and calculated values were used during the vehicle build-up. A final measurement of Zcg was made for each vehicle before it's maiden flight. The Zcg's on vehicles 131 and 132 were measured just prior to shipment from JSC after the vehicle was outfitted with equipment. A second standalone Zcg test was performed at DFRC on vehicle 132. A single standalone Zcg test was performed on vehicle 131-R at DFRC. The three-point suspension method was used at JSC since a facility that could accommodate this type of measurement was available. An attempt was made to do a four-point suspension test from the B-52 pylon at DFRC, but the results were inconclusive at best. Two other Zcg tests were performed that involved either hanging a weight box on the vehicle or using a lifting fixture that could support the vehicle at different pitch angles.

Other weight and balance tests involved using three load cells between the vehicle's jackpoints and jackstands or on the three in-ground platform scales within the Weight and Balance Facility at Edward's Air Force Base. In these cases, the Zcg was calculated based on propagation from a previously measured value.

THREE LOAD CELL MEASUREMENT

One of the easiest ways of obtaining the vehicle weight and balance properties is to locate compressive load cells between the vehicle and jackstands. Each of the atmospheric test vehicles had three jackpoints. One in the nose region and two just forward of the body flaps. The location of these jackpoints was known with high precision. The load cells are located on top of three jackstands and the vehicle is lowered onto the load cells. Care must be taken to ensure that side loads are not introduced into the load cells. The vehicle must then be leveled in pitch in roll. Figure 2 shows the force diagram for this type of test. The sum of the three load cells provides the vehicle weight. Summing the moments provides the data necessary to calculate the Xcg and Ycg.

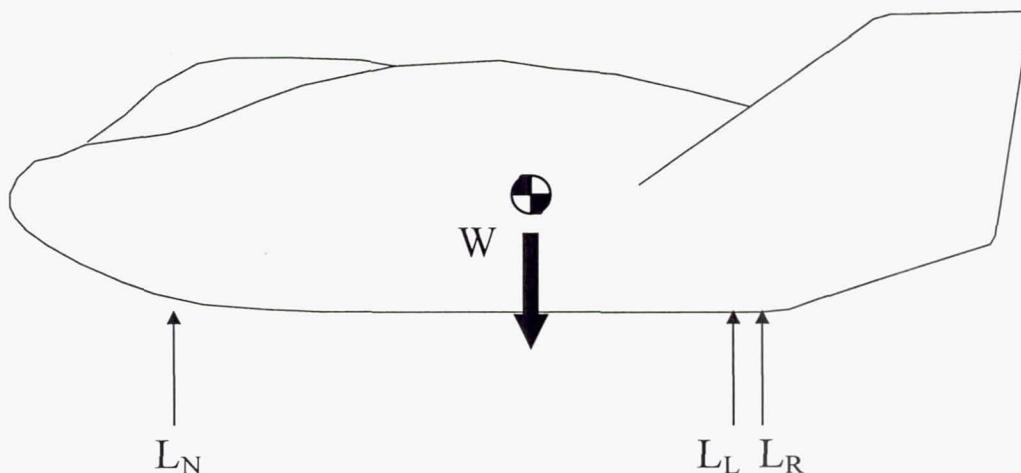


Figure 2 – Weight and Balance Force Diagram

The computational equations follow:

Weight, X_{cg}, and Y_{cg}

$$W = L_N + L_L + L_R$$

$$X_{cg} = (l_N * L_N + l_L * L_L + l_R * L_R) / W$$

$$Y_{cg} = (d_N * L_N + d_L * L_L + d_R * L_R) / W$$

Where:

L_N , L_L , and L_R = load cell readings

l_N , l_L , and l_R = longitudinal distances from the origin

d_N , d_L , and d_R = lateral distances from the origin

The three equations have three unknowns that are readily solved. This is one of the simplest tests to perform and the results are accurate and very repeatable. In a typical test, the vehicle would be leveled and a measurement was taken. The vehicle orientation was then changed by lowering or raising two of the jackstands. The vehicle was then re-leveled using a bubble-level installed within the vehicle and another measurement was taken. Sometimes this was repeated a third time as well. The vehicle weight was repeatable in many cases to within 5 pounds, but in some cases, it was as high as 15 pounds. The X_{cg} and Y_{cg} were repeatable to within a tenth of an inch.

THREE PLATFORM SCALE MEASUREMENT

Measuring a vehicle's weight and balance on three platform scales is very similar to the measurement described in the previous section. However, in this case the load cells are placed below the jackstands. This can be done in two different ways. The jackstands can be placed on portable aircraft platform scales or the vehicle can be brought to a facility where the scales are

integrated into the facility floor. These are just two implementations of the same concept as the physics of the problem are the same. The X-38 Project had access to the Weight and Balance Facility at Edward's Air Force Base. This facility allows aircraft to be positioned onto the three in-ground scales for weight and balance purposes. Since the X-38 vehicles did not have landing gear that could support its weight the vehicle was supported by jackstands in the same manner as described by the previous section. In this case, the jackstands must be weighed separately before or afterwards so their weight can be subtracted out of the total weight. Figure 3 shows vehicle 131-R in the Weight and Balance Facility. The three lighter shaded areas shown on the floor in this picture are the in-ground scale weighing surfaces.

This type of test was very simple to perform as well and the results were just as good if not better than the results of doing the test with loads cells between the vehicle and the jackstands. There was more overhead with this test because the facility had to be reserved and the vehicle had to be transported to the facility. The scales at the Edward's Weight and Balance Facility were advertised to be accurate to within 0.07% of the measured weight, which translates into 10 to 13 pounds for the vehicles weighed. The results from two consecutive tests were repeatable to within 10 pounds and a tenth of an inch in X_{cg} and Y_{cg} .



Figure 3 – Weight and Balance Using In-ground Scales

THREE-POINT SUSPENSION METHOD

The three-point suspension test provides the ability to measure weight, and all three-axes of the CG. When the vehicle is suspended in a level orientation the sum of the three load cells provide the weight. Summing moments also allows the calculation of the Xcg and Ycg. By taking measurements at various nose up and nose down attitudes the Zcg can be calculated.

Figure 4 shows the load diagram for the vehicle suspended in a level orientation. Changing the pitch attitude for Zcg determination is shown in figure 5. To reduce the introduction of error sources care must be taken to keep the vehicle level in roll and to ensure that the suspension cables are vertical. Figure 6 depicts an actual test performed at JSC on vehicle 131.

The process is to take a measurement with the vehicle suspended in a level orientation. Weight, Xcg, and Ycg can be calculated by summing forces and moments in a manner similar to the case when the vehicle is supported by jackstands. The same three equations are employed again. Now the vehicle is articulated in a nose up or nose down attitude and another measurement is taken. The Zcg is calculated based on the trigonometry of the configuration and accurate knowledge of the pitch angle. Most of the tests were performed before there were any avionics installed in the vehicle so the pitch angles were measured with a digital inclinometer taped on the side of the vehicle. Another inclinometer or bubble level was used to ensure that the vehicle remained level in roll.

The computational equations follow:

Weight, Xcg, and Ycg

$$W = L_N + L_L + L_R$$

$$X_{cg} = (l_N * L_N + l_L * L_L + l_R * L_R) / W$$

$$Y_{cg} = (d_N * L_N + d_L * L_L + d_R * L_R) / W$$

Zcg Determination at 15° Angle

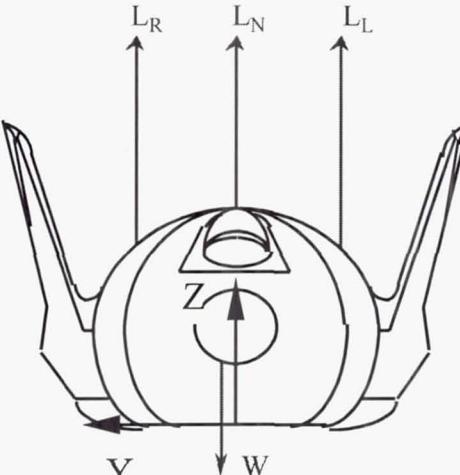
$$\Sigma M_0 = 0 = (N * A) - (W * B) + (A_L + A_R) * C$$

Where:

$$A = 29.5 \cos 15^\circ - 44.5 \sin 15^\circ = 17.0"$$

$$B = X_{cg} \cos 15^\circ - Z_{cg} \sin 15^\circ$$

$$C = 217.0 \cos 15^\circ - 45.3 \sin 15^\circ = 197.9"$$



Ycg Determination

$$\Sigma F_0 = 0 = L_N + L_L + L_R - W$$

$$\Sigma M_0 = 0 = (W * Y_{cg}) + (L_L * 36.6) - (L_R * 36.6)$$

2 Equations, 2 Unknowns (W, Ycg)

Figure 4 –3-Point Suspension Load Diagram

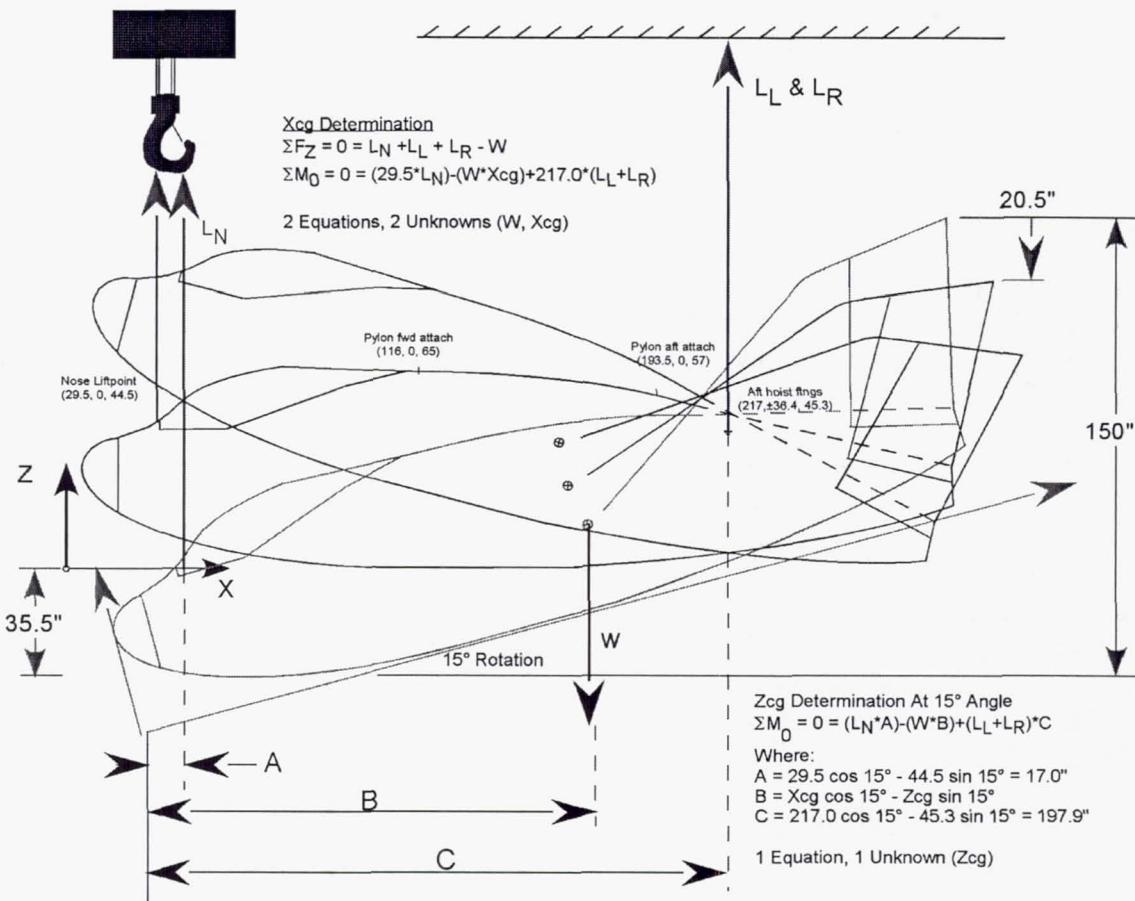


Figure 5 – 3-Point Suspension Showing Articulation for Zcg Determination

Like the three-point support methods the level measurements for weight, X_{cg}, and Y_{cg} measurements were very repeatable and within the same accuracies. There was some variation in the measured weights in the nose up and nose down orientations, but these values were discarded and just those obtained in the level measurements were used. The values calculated for Z_{cg} varied more due to the small angles that were achieved in the tests. The largest angle achieved during any of the tests was on the order of 15 degrees. Larger angle would displace the Z_{cg} further, which would aid in providing more accuracy in the test. The variation in the calculated Z_{cg} between two consecutive tests was as high as two inches, but was typically less than an inch.

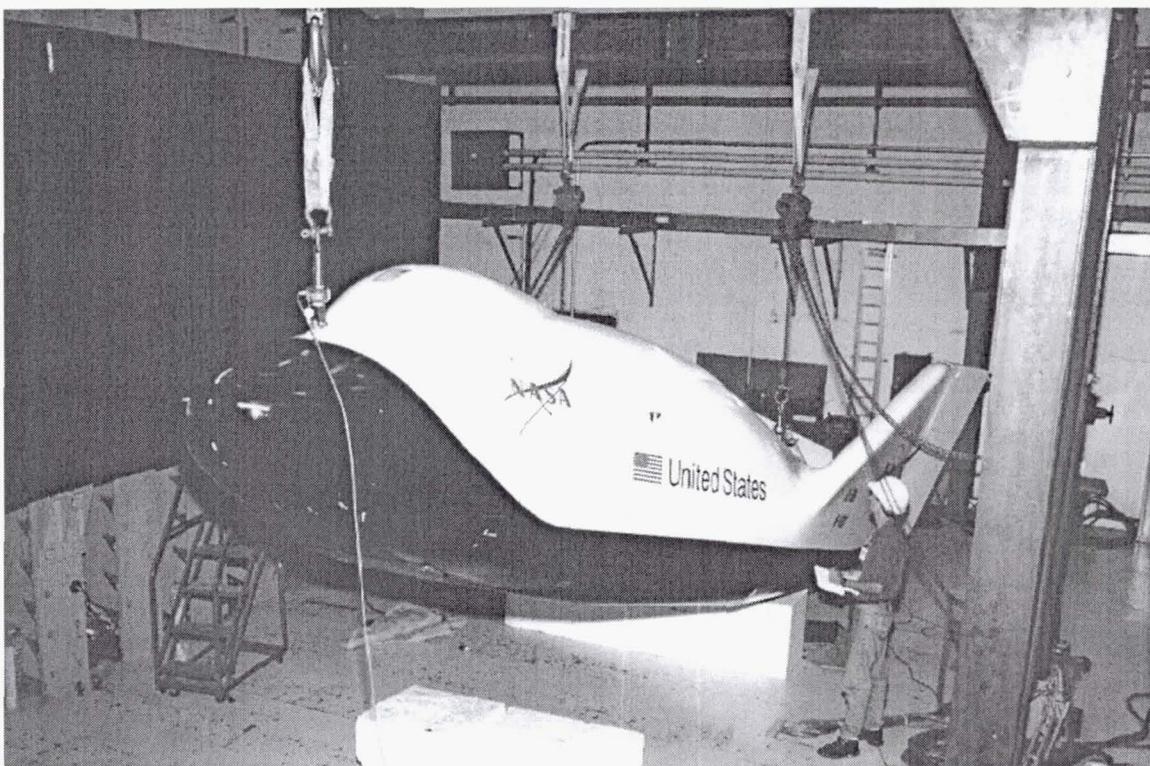


Figure 6 – 3-Point Suspension Nose Up

FOUR-POINT SUSPENSION METHOD

Another method was attempted to measure the Zcg on the atmospheric vehicles by suspending the vehicle from the four B-52 pylon hoist points. Four chain hoists were used to raise and attach the vehicles to the B-52 pylon. Figure 7 depicts vehicle 131 hanging from chain hoists on the wing of the B-52. A test similar to the three-point suspension test was performed where the vehicle was suspended in a level configuration and then articulated to nose up and nose down positions. Multiple nose up and nose down positions were measured and the vehicle was returned to level and a final measurement was taken. The first thing to note with this test arrangement is that the vehicle is over constrained. Four suspension points make it easy to place bending and twisting loads on the vehicle without knowing it. This is due to the vehicle fuselage not being very stiff. Therefore, it was impossible to tell when side loads were being placed on the load cells. None of the measurements taken was repeatable so this test was never performed again and the data was not used for any future analyses.



Figure 7 – 4-Point Suspension Showing Nose Up

SINGLE-POINT SUSPENSION ZCG MEASUREMENT

Two different tests were performed where the vehicle was suspended by a single point at different hang angles in order to determine the Zcg. The first test involved hanging a weight tub at a known location where known weight was added and the change in pitch was measured. The second test involved using a lifting brace with multiple lift points.

Single-Point Suspension with a Weight Tub

This test involved lifting the vehicle and leveling it out in pitch and roll with shot bags placed at measured locations. A weight tub was then attached to the rear of the vehicle and weight was added incrementally to the weight tub. Figure 8 shows the geometry associated with this test while figure 9 shows vehicle 132 being tested in this manner. Each time a known weight was added to the tub the associated change in vehicle pitch angle was measured. The resulting pitch change caused by the change in weight at a known location allows the calculation of vehicle Zcg. The change in pitch angle was measured by the onboard inertial navigation system (INS). The INS utilized ring-laser gyros and small changes in pitch attitude could be measured accurately.

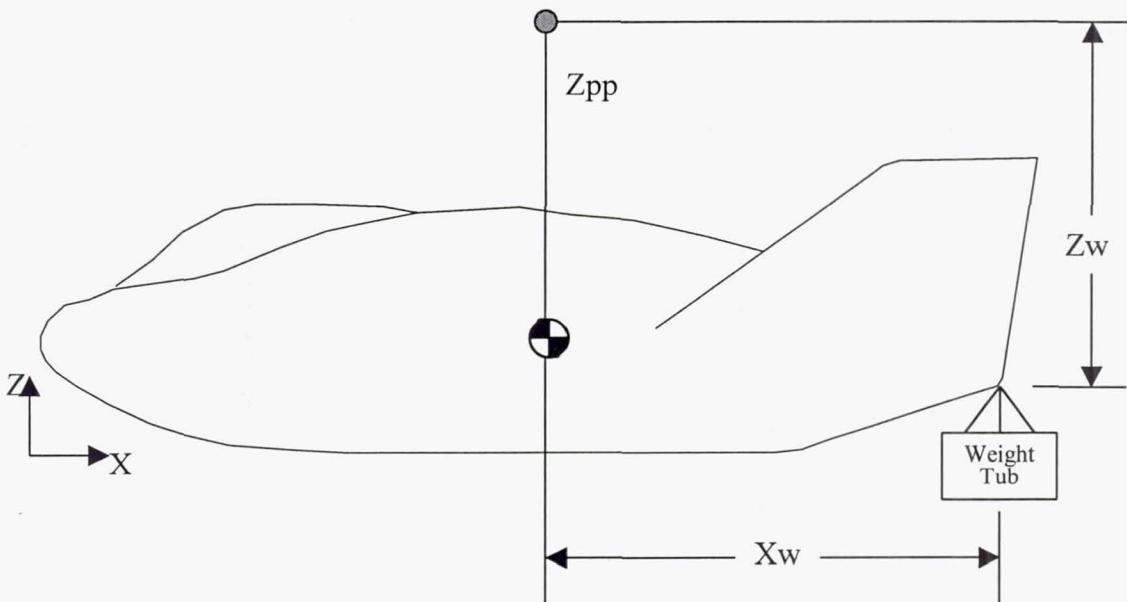


Figure 8 – Geometry for Single-Point Suspension with a Weight Tub

The computational equation for the weight tub method follows:

$$Z_{cg} = Z_{pp} - \frac{w}{W} \left(\frac{X_w}{\tan \Theta} - Z_w \right)$$

Where:

Z_{pp} = the height of the pivot point in the vehicle coordinate system

w = the delta weight added

W = the vehicle and fixturing weight

X_w = the longitudinal distance from the pivot point to the weight tub

Z_w = the vertical distance from the pivot point to the weight tub

In the test performed on vehicle 132, the vehicle was leveled in pitch and roll and then the weight tub and weights were added in ten increments of approximately 100 pounds each. The final total weight of the tub and shot bags was 996 pounds and the associated pitch angle was 10.42 degrees. The weights were then removed incrementally and the pitch angles were recorded. The results of this test were poor and the test configuration was disassembled before the data was reduced. The Z_{cg} calculated from the first ten data points ranged from 51.5 to 52.7 inches. The last ten data points recorded when the weights were being removed then deviated from 53.3 to 69.5 inches showing there was some hysteresis in the system. The reader will note that any error in a small angle measured by the system is amplified significantly when the $\tan \Theta$ term is considered. So it was determined that the last ten data points should be discarded. However, the predicted value for Z_{cg} was 26.6 inch so even the first 10 data points could not be used. There must have been a flaw in one of the distance measurements so the data from the test was never used for any future analyses.



Figure 9 – Single-Point Suspension Zcg Determination with a Weight Tub

Single-Point Suspension with Multiple Lift Points

The second method used in measuring Zcg from a single-point suspension utilized a lifting brace that had three holes in it. The geometry associated with the special lifting brace is depicted in figure 10 while figure 11 shows vehicle 131-R being tested in this manner. The lifting brace was designed to lift the vehicle in a level orientation when the center hole was used. Therefore, this hole was located as close as possible to lie directly above the Xcg. This hole was used when the vehicle was initially lifted and shot bags were used to null out any pitch and roll angles.

The vehicle was then lowered back down onto foam blocks and the lifting brace was rigged to lift the vehicle from the forward hole. The vehicle will tilt in pitch until the CG is directly below the lifting point. Therefore, when the forward hole on the lifting brace is used the vehicle will be pitched in a nose up attitude. Conversely, when the aft lifting brace hole is used the vehicle will be lifted in a nose down attitude.

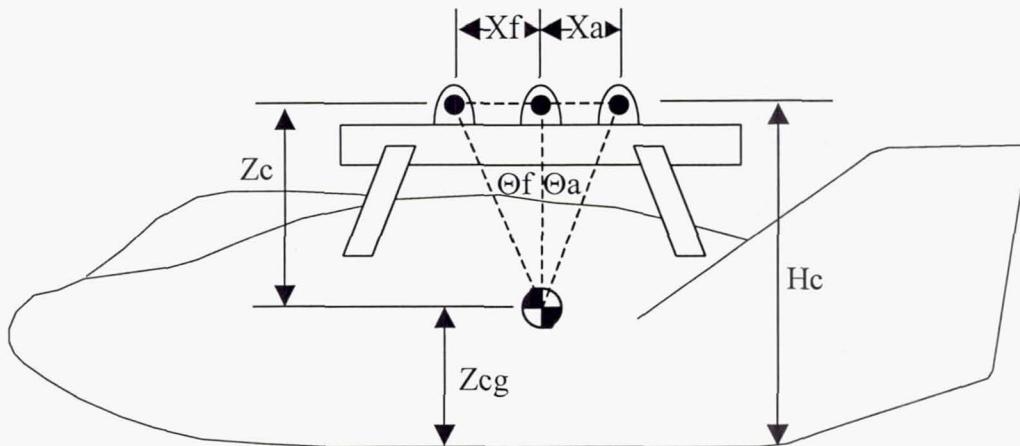


Figure 10 – Geometry for Single-Point Suspension with Multiple Lift Points

The computational equations for the multiple lift point method follow:

$$Z_{cg} = H_c - \frac{X_f}{\tan \Theta_f} \quad (\text{for the forward hole})$$

$$Z_{cg} = H_c - \frac{X_a}{\tan \Theta_a} \quad (\text{for the aft hole})$$

Where:

Hc = the vertical distance from water line zero to the suspension point hole

Xf = the longitudinal distance from the center hole to the forward hole

Xa = the longitudinal distance from the center hole to the aft hole

Θ_f = the resulting pitch angle when the forward lift hole is used

Θ_a = the resulting pitch angle when the aft lift hole is used

The distance between the holes on the lifting brace, Xf and Xa, are known prior to the test. The distance from water line zero (the bottom of the vehicle) to the pivot plane of the lifting holes is measured prior to the test. The change in pitch angle can be measured with a digital inclinometer or with the onboard INS. Given the measured distances and pitch angle, simple trigonometry is used to calculate the Zcg.

The results achieved with this test were better than those achieved with the weight tub method. The nose up pitch angle was measured to be 18.932 degrees with the INS and the nose down angle was measured at 19.318 degrees. The resultant Zcg's calculated with these two pitch angles were 33.46 and 34.52 inches respectively. This represented a spread of just over an inch and the resulting values were close to the values predicted for this vehicle.

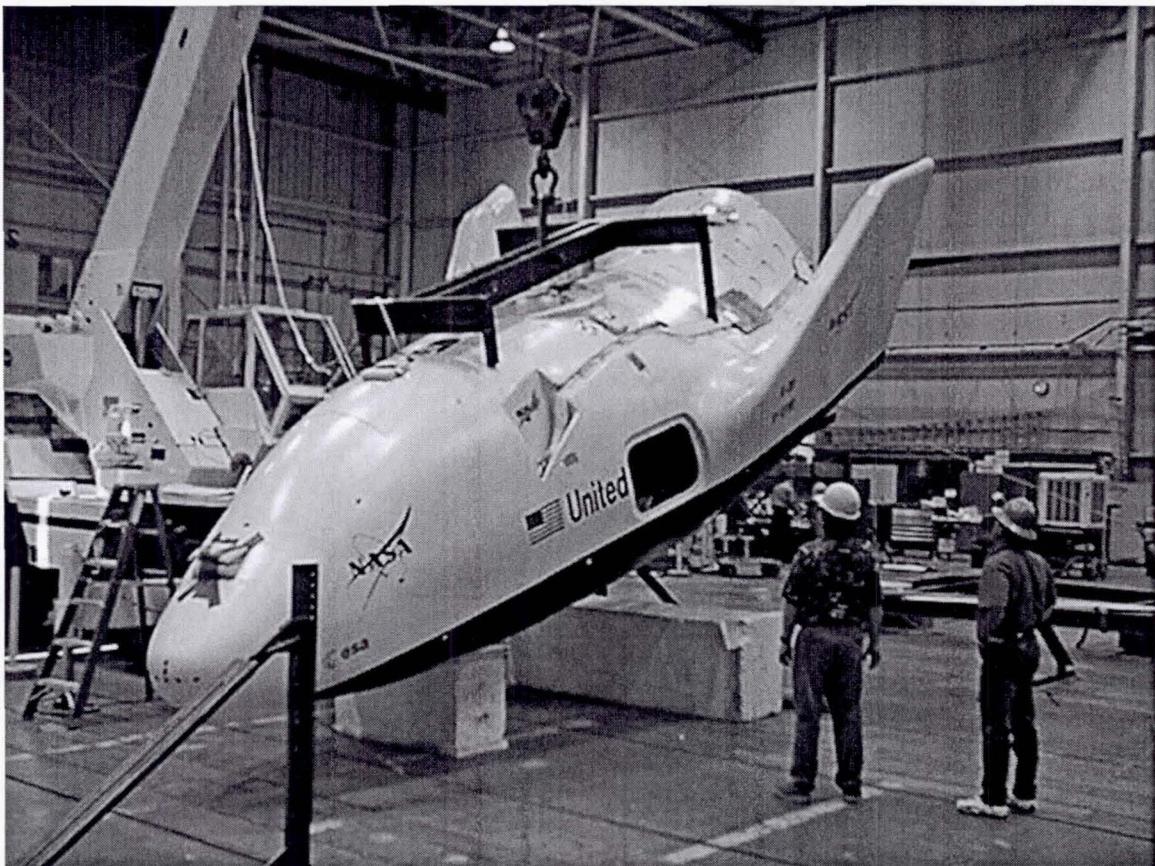


Figure 11 – Single-Point Suspension Zcg Determination with Multiple Lift Points

METHOD COMPARISON

The best results for weight and balance were obtained from the three-point methods. This includes suspension and support methods. The four-point suspension method over constrained the vehicle and the results were not repeatable. A single-point suspension method could be employed to obtain weight, X_{cg}, and Y_{cg}, but this was never used. To do this the vehicle would be lifted in a near level orientation with a single load cell used to determine the vehicle weight. Known weights would then be located on the vehicle until it is balanced in pitch and roll. Once the locations of the weights were measured, the X_{cg} and Y_{cg} could be calculated. This method is not as accurate as a traditional three-point system since new error sources are being introduced. Accurate location of the applied balancing weights can be hard to measure. It is also more difficult to know when the vehicle is perfectly level in pitch and roll while balanced under a single-point.

Obtaining and accurate Z_{cg} measurement proved to be extremely difficult. Precise variations in pitch were made using the onboard INS, but most distance measurements were made using a tape measure from known vehicle locations, which introduced error. If the tests were performed again it is recommended to measure distances with a laser measurement system or another system with more accuracy. The three-point suspension is the best method for Z_{cg} determination.

INERTIA MEASUREMENT

Several inertia tests were completed on the atmospheric vehicles. The traditional tests measured I_{xx} , I_{yy} , I_{zz} , and I_{xz} . A new method for measuring the complete mass properties tensor called DIM was also performed. This method obtained the vehicle weight, CG, inertias, and products of inertias all in one test. Each test will be described in detail in the following sections.

BIFILAR IZZ MEASUREMENT

A simple bifilar test was performed on vehicle 132 to obtain a measured value to compare to the estimated value. This was not a formal test. The vehicle was undergoing a free-free GN&C test at JSC to determine the interactions between the flight control system and the structural response when moving the aerosurfaces. The vehicle was suspended from the two B-52 pylon interfaces by cables attached to two springs in a bifilar arrangement. While the vehicle was suspended in this orientation two engineers applied a coupled load at the nose and tail of the vehicle. The intent was to provide a yawing moment on the vehicle without also inducing roll or pitch. The subsequent oscillations in yaw were measured by a stopwatch.

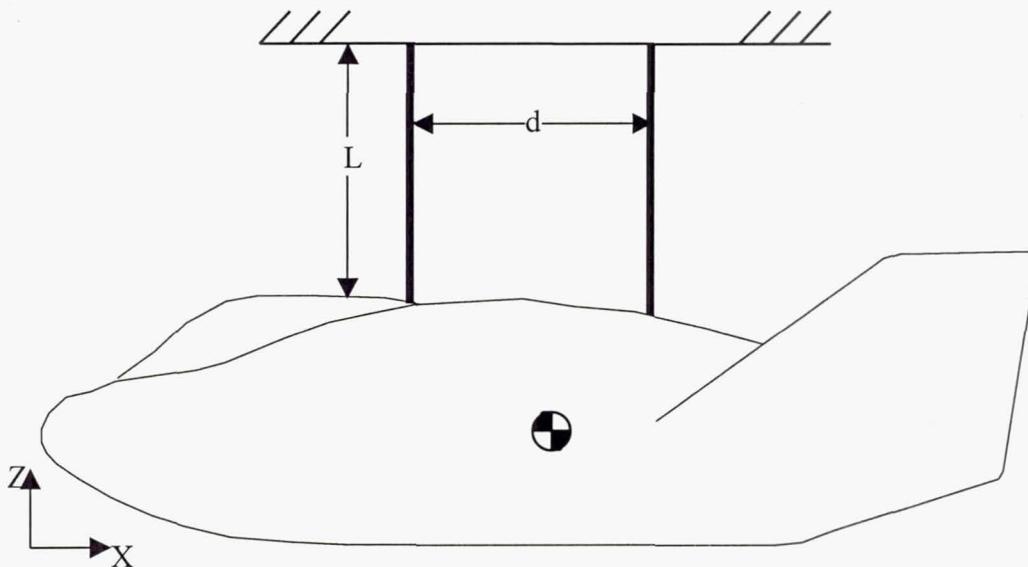


Figure 12 – Bifilar Yaw Inertia Measurement

The equation used to compute Izz from this configuration follows ²:

$$I_{zz} = m \left(\frac{Td}{4\pi} \sqrt{\frac{g}{L}} \right)^2$$

Where:

- m = vehicle mass in slugs
- T = period
- d = distance between bifilar cables
- L = length of the pendulum
- g = gravitational constant

This was a quick and simple test used to calibrate the estimated value of Izz. The test was not performed in a tightly controlled manner since a more formal test would be performed once the vehicle was delivered to DFRC. It was valuable in that it showed that the predicted value for Izz was fairly close to the measured value, which gave some confidence in the other inertia estimates as well. The predicted value for the test configuration was 17,923 slug-ft² and the measured value was 17,199 slug-ft², which is a difference of 4.2%. The estimate going into the test was based on results from an Izz test performed on vehicle 131 previously (described in the next section) and the results from this test were used to adjust the vehicle estimates to be used going into a more detailed test to be performed at DFRC.

SINGLE-POINT SUSPENSION IZZ AND IXZ MEASUREMENT

The first test undertaken to measure a component of inertia was the single-point suspension method for obtaining Izz and Ixz. Vehicle 131 did not have an active flight control system so the value of Ixz became critical to the success of the first flight. Simulations conducted by flight dynamics personnel showed that there was a chance that the vehicle could lose control due to the wake of the B-52 if the value of Ixz was not zero or negative. Therefore, Ixz needed to be measured and corrected if the measured value was not low enough.

The arrangement for this test is shown in figures 13 and 14. The vehicle is suspended by a crane using a single-point lifting brace and a rigid beam is attached to the bottom of the vehicle below the Xcg. Floor stands are located twelve feet apart from each other at the four corners of the vehicle. Springs are then attached to these floor stands and the horizontal beam as shown in figures 13 and 14. The floor stands have several vertical heights at which the springs may be attached to provide for tests at several different spring angles. The angle of the spring plane is changed by using different hole selections between the forward and rear stanchions.

To obtain Izz, and subsequently Ixz, the vehicle must be measured at a number of spring orientations. The springs are used to oscillate the vehicle about the yaw axis. If the value of Ixz is not zero, the springs will cause the vehicle to oscillate in roll as well as yaw when the spring action plane is level. The plane in which the springs applied load to the vehicle is varied in pitch until there is no longer a roll oscillation. It is at this angle that the values of Izz and Ixz can be computed.

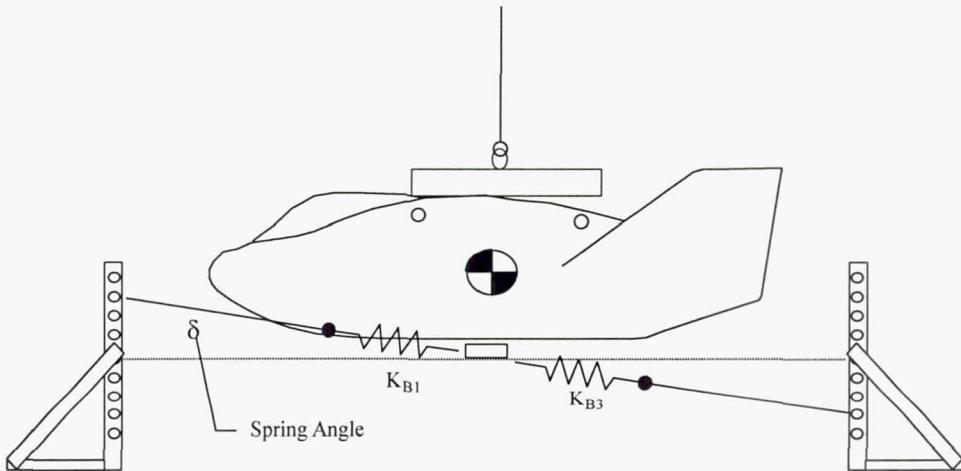


Figure 13 – Izz and Ixz Measurement Test Arrangement, Side View

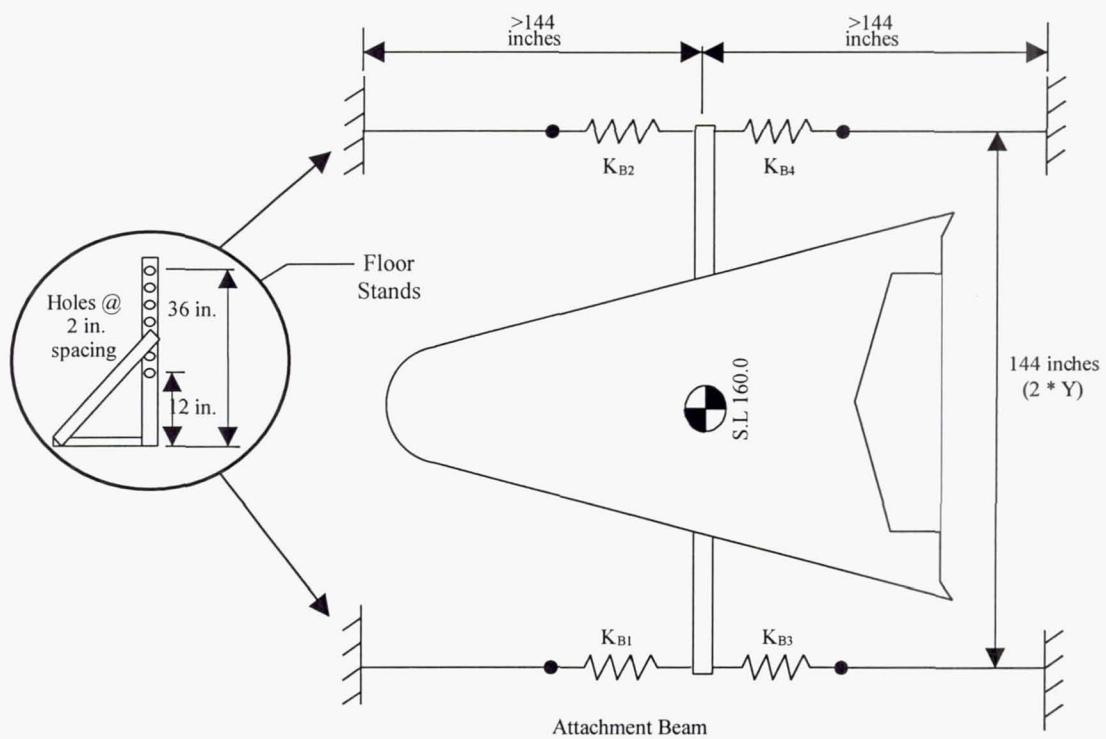


Figure 14 – Izz and Ixz Measurement Test Arrangement, Plan View

The equations used to compute Izz and Ixz from this configuration follow:

$$Izz = Y^2 * (K_{B1} + K_{B2} + K_{B3} + K_{B4}) * \cos(\delta_0) / \omega^2$$

$$Ixz = Izz * \tan(\delta_0)$$

Where:

ω = the yaw oscillation frequency (in rad/sec),

Y = the lateral distance from the vehicle centerline to the spring attachment points,

δ_0 = the spring angle at which the roll rate to yaw rate ratio is zero

K terms = the four spring constants in lbs/ft

The results achieved from these tests were very good and the test points were very repeatable. A plot was made showing the effect of the spring plane angle, δ , on the roll/yaw ratio and the resulting line was straight showing excellent correlation of the data. The angle at which the roll/yaw ratio goes through zero is obtained from the curve fit for the plot data. The vehicle INS provided continuous time histories of pitch rate, roll rate, and yaw rate, which were recorded and displayed on a ground data acquisition system. It could be seen on the plots provided by the data acquisition system when the roll rate oscillations became very small. This time history of the data at this spring angle was nearly a straight line. An error analysis based on the test calculated the measurement accuracy on Izz to be ± 282 slug-ft 2 and ± 67 slug-ft 2 on Ixz. Vehicle 132 is shown in figure 15 undergoing this type of test.

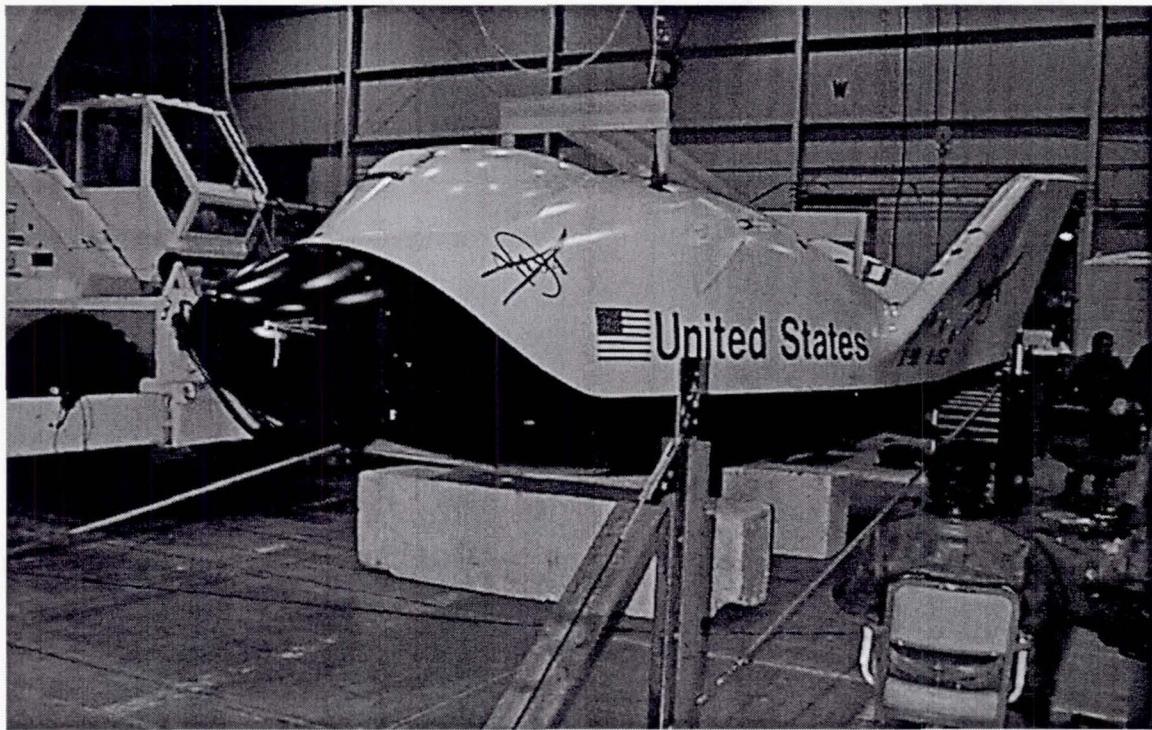


Figure 15 – Vehicle 132 Undergoing Izz and Ixz Measurement Test

SPRING TABLE IXX AND IYY MEASUREMENT

Using a spring table to measure I_{xx} and I_{yy} was first employed on vehicle 132. This test was not performed on vehicle 131 because the flight time before parachute extraction was too short for aerodynamic parameter identification. Vehicle 132 had an active flight control system and longer free-flight times. Identification of the aerodynamic parameters was desired so accurate knowledge of the mass properties was required. Therefore, I_{xx} and I_{yy} were measured in addition to I_{zz} and I_{xz} .

The method employed to measure I_{xx} and I_{yy} was a spring table as depicted in figure 16. This method utilizes knife-edges on two sides of the table and springs on the other two sides. The vehicle is placed on top of the table so the CG is directly above the line formed by the two knife-edges. The vehicle is then allowed to oscillate back and forth due to the influence of the springs. The inertia can be calculated by using calibrated springs and timing the oscillations. If the knife-edges are placed below the X_{cg} and the vehicle is oscillated in pitch, I_{yy} can be determined. If the knife-edges are placed below the Y_{cg} and the vehicle is oscillated in roll, I_{xx} can be determined. The vehicle and table arrangement was allowed to oscillate for 50 to 100 cycles while being timed with a stopwatch. The vehicle was removed and the test was repeated for the table and spring arrangement alone. The measurement of the table by itself is required to remove its contribution to the inertia from the measurement with the vehicle.

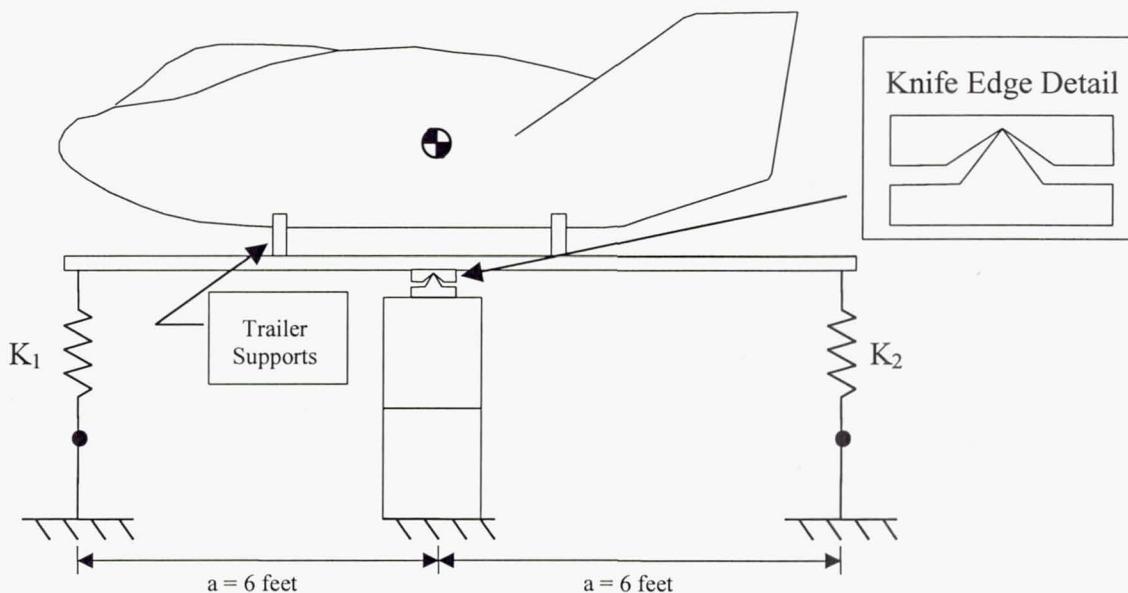


Figure 16 – I_{xx} and I_{yy} Measurement Test Arrangement

The basic equation governing the frequency of the oscillation is shown below³:

$$\omega^2 = [(K_1 + K_2) * a^2 - W_c * H_c - W_v * H_v] / I_{KE}$$

where:

- K_1 = Total left/forward spring constant
 K_2 = Total right/aft spring constant
 a = Moment arm to spring attachment points
 W_c = Weight of the cradle
 H_c = Height of the cradle above the knife-edge
 W_v = Weight of the vehicle
 H_v = Height of the vehicle above the knife-edge
 I_{KE} = Inertia about the knife edge

The total inertia of the assembly about the knife-edge may be computed rearranging the previous equation:

$$I_{KE} = [(K_1 + K_2) * a^2 - W_c * H_c - W_v * H_v] / \omega^2$$

To obtain the inertia of the vehicle about its own center of gravity, the following equation may be employed:

$$I_v = I_{KE} - I_c - m_v * H_v^2$$

where:

- I_c = Inertia of the cradle about the knife-edge
 m_v = Mass of the vehicle

When the knife-edges are located under the Xcg then I_{yy} can be substituted for I_v in the equation above since the pitch inertia is being measured. Conversely, if the knife-edges are located below the Ycg then the roll inertia is being measured and I_{xx} can be substituted for I_v .

The results of the tests utilizing the spring table were very good and the test points were very repeatable. The predicted value for I_{xx} for vehicle 132 going into the test was 3,955 slug-ft² and the measured value was $3,817 \pm 560$ slug-ft² including the error analysis. The predicted value for I_{yy} was even closer to the measured value. The I_{yy} prediction was 20,910 slug-ft² and the measured value was $21,076 \pm 908$ slug-ft². Figure 17 shows vehicle 132 just prior to the I_{xx} test.

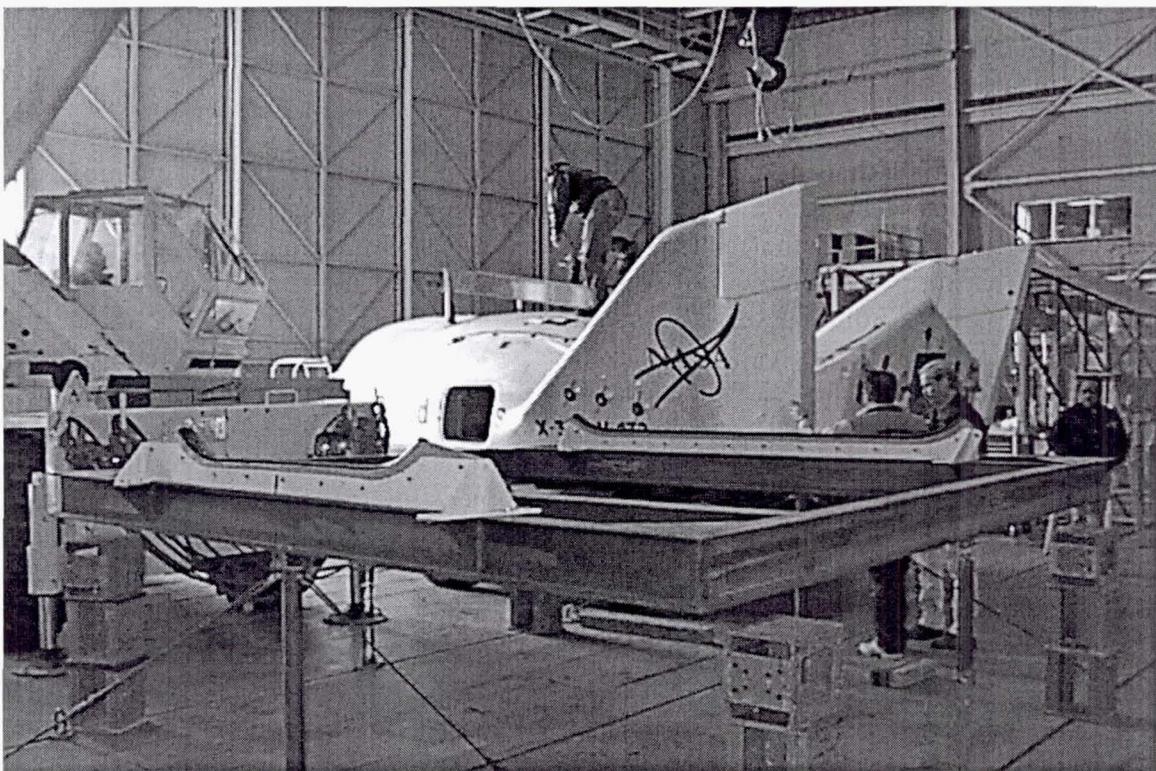


Figure 17 – Ixx and Iyy Spring Table Arrangement

DYNAMIC INERTIA METHOD (DIM)

The DIM method for determining the full mass properties tensor was developed at the University of Cincinnati. This method was perfected in determining the mass properties of small rigid-body objects. The first application of this method to an object as large and complex as an aircraft was performed on vehicle 132. This test was performed under a small business innovative research grant at DFRC. Since vehicle 132 was the first vehicle where the weight, CG, and inertias were measured by traditional means in over 30 years the opportunity was taken to immediately measure the mass properties using DIM before any vehicle configuration changes were made. It was hoped that any problems encountered in using this method would be uncovered so the technique could be matured for use on future vehicles.

Dynamic forces are applied to an object and its resulting rigid body acceleration is measured. Three 6-degree-of-freedom (DOF) load cells were used to measure all forces and moments applied to the vehicle including support forces. An array of linear accelerometers is also used to measure the 6 DOF acceleration of the test article. In order for this technique to work the bending modes of the vehicle configuration must be known so that data can be filtered out of the resulting data.

The vehicle is softly supported at the three jackpoints by pneumatic isolators with the 6-DOF load cells positioned between the soft support and the vehicle jackpoint. Forces were applied to

the vehicle using an electromagnetic shaker or instrumented impact hammer. Using Newton's Second Law ($F=ma$), the mass properties were derived by measuring the forces applied and the resulting accelerations.

The results were initially hard to derive using this method because of the flexible modes of the vehicle and supports.  There was a large mass within the vehicle which was causing a strong resonance at ~ 13 Hz that was not anticipated. This effect was attributed to either the packed parafoil or the backup parachute both of which were not installed during the vehicle modal test performed at JSC. The soft supports also had modes near 6 Hz, which could not be accounted for. This left the region between 7 and 12 Hz where the assumptions of the method were met¹. When the results were finally derived they compared favorably with the values obtained via traditional testing, but there was still room for improvement. Therefore, the test was repeated on vehicle 131-R in parallel with the traditional mass properties testing. The test results were much better from the second round of tests where lesson learned from the first test were applied. The ultimate goal of the DIM testing from the perspective of NASA was to mature the technique to the point where it could be used as a standalone test to measure mass properties in conjunction with a vehicle modal test. This would avoid all of the lifting and fixturing required for traditional mass properties testing.

SUMMARY

Over thirty major mass properties tests were completed on the family of X-38 vehicles. Most of the tests used traditional techniques developed many years before, but some of the tests broke new ground. Many of the tests were used by NASA to measure the inertias on similar vehicles, but these tests had not been employed for over 25 years. The results of the tests provided the confidence for the X-38 Project team to pursue a successful flight testing program. The measured mass properties also provided the means for the aerodynamicists to derive the aerodynamic parameters obtained in the flight tests.

In the process of completing all of the different mass property tests, the X-38 Project obtained a well trained test team. This included all areas of testing including theory, application, procedures, and execution. The first time a complete suite of tests (weight, X_{cg} , Y_{cg} , Z_{cg} , I_{xx} , I_{yy} , I_{zz} , I_{xz}) were performed at DFRC it took the test team nearly two weeks to complete all of the tests. When the same suite of tests was performed for the last time on vehicle 131-R it required only three to four days.

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ABOUT THE AUTHOR

Wayne L. Peterson is an aerospace engineer at the NASA Johnson Space Center in Houston, Texas where he performs advanced space transportation studies with special emphasis on mass properties and configuration design. He was involved in the X-38 Project from it's inception in 1995 to it's termination in 2003. During that time he held a variety of positions including Recovery Lead and Vehicle Manager for the spaceflight test vehicle in addition to completing the mass properties estimations, projections, and measurements on all of the X-38 vehicles.

He received his Bachelors Degree in Aerospace Engineering from Texas A&M University in 1985. His hobbies include softball, flag football, skiing (water & snow), drumming, music, and Internet development. He has been a member of the SAWE since 1986, the SAWE International Webmaster since it's inception in 1995, and is a Fellow in the society.